

Impact of future Arctic shipping on high-latitude black carbon deposition

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[1] The retreat of Arctic sea ice has led to renewed calls to exploit Arctic shipping routes. The diversion of ship traffic through the Arctic will shorten shipping routes and possibly reduce global shipping emissions. However, deposition of black carbon (BC) aerosol emitted by additional Arctic ships could cause a reduction in the albedo of snow and ice, accelerating snowmelt and sea ice loss. Here we use recently compiled Arctic shipping emission inventories for 2004 and 2050 together with a global aerosol model to quantify the contribution of future Arctic shipping to high-latitude BC deposition. Our results show that Arctic shipping in 2050 will contribute less than 1% to the total BC deposition north of 60°N due to the much greater relative contribution of BC transported from non-shipping sources at lower latitudes. We suggest that regulation of the Arctic shipping industry will be an insufficient control on high-latitude BC deposition. **Citation:** Browse, J., K. S. Carslaw, A. Schmidt, and J. J. Corbett (2013), Impact of future Arctic shipping on high-latitude black carbon deposition, *Geophys. Res. Lett.*, 40, 4459–4463, doi:10.1002/grl.50876.

1. Introduction

[2] The dramatic decline in Arctic sea ice extent over the past few decades has led to growth of the existing industry and renewed interest in trans-Arctic shipping [Corbett *et al.*, 2010]. Expansion of Arctic shipping could reduce net global ship emissions by decreasing traffic through the longer sea routes. However, there is concern that an increase in anthropogenic activity in the Arctic could contribute to regional climate forcing [Ødemark *et al.*, 2012; Dalsøren *et al.*, 2007].

[3] Emissions from Arctic ships are likely to increase the mass of black carbon (BC) deposited on sea ice and snow surfaces. BC deposition has been identified as a particularly efficient forcing mechanism that can increase surface temperatures and accelerate snowmelt [Flanner, 2013].

[4] New aerosol emission inventories for the Arctic region [Corbett *et al.*, 2010] allow the effect of increased ship traffic on Arctic BC deposition to be quantified for the first time. Here we use these inventories together with a global aerosol microphysics model to calculate the increase in BC deposition attributable to the growth of the Arctic

shipping industry between 2004 and 2050 under different economic and political scenarios.

2. Model Description

[5] We use a global model of aerosol processes (GLOMAP) [Mann *et al.*, 2010], coupled to the chemical transport model TOMCAT [Breider *et al.*, 2010]. The model was run at a resolution of $2.8^\circ \times 2.8^\circ$ with 31 vertical levels extending from the surface to 10 hPa. GLOMAP uses a two-moment size-resolving scheme to calculate particle mass and number distribution in four variable size lognormal modes: nucleation (diameter ~ 3 – 15 nm), Aitken, (~ 10 – 50 nm), accumulation (~ 50 – 200 nm), and coarse (~ 1000 nm).

[6] Anthropogenic BC is emitted into a lognormal mode with a standard deviation of 1.59 and geometric mean diameter of 60 nm [Stier *et al.*, 2005]. At emission, BC particles are assumed to be water insoluble but can become active in cloud drop formation as soluble material accumulates on them [Mann *et al.*, 2010]. After BC particles become cloud active, they are more efficiently wet scavenged, which accounts for 80% of modeled BC deposition [Mann *et al.*, 2010].

[7] Recent improvements to the wet deposition scheme in GLOMAP mean that the model is now able to reproduce the observed seasonality and magnitude of atmospheric BC mass concentrations at Arctic ground sites well [Browse *et al.*, 2012]. As GLOMAP does not diagnose snow depth, direct comparison with deposition measurements is not possible as the deposition is typically reported as the BC to water ratio within a snow layer [Doherty *et al.*, 2010]. However, comparison with a similar study [Skeie *et al.*, 2011] capable of simulating snow burden is possible.

[8] The total deposited mass of BC north of 65°N in GLOMAP at the end of April (22 Gg) is approximately double that calculated for 2004 in Skeie *et al.* [2011]. Anthropogenic and wildfire BC emissions north of 40°N in the two studies are similar (1 and 0.2 Tg) as is the BC deposition from wildfires (0.7 and 1 Gg). Thus, the greater BC mass deposited in GLOMAP is likely attributable to more efficient transport from lower latitudes, a hypothesis supported by the significant underestimation (factor of 10) in Skeie *et al.* [2011] of springtime BC aerosol concentrations (which are sourced predominantly from lower latitudes) at the ground stations Barrow (71°N, 156°W) and Zeppelin Mountain (78°N, 12°E), which are reproduced well in GLOMAP [Browse *et al.*, 2012].

3. Present-Day Emission Inventories

[9] This study makes use of the detailed Arctic shipping emission inventories of Corbett *et al.* [2010]. Emission rates

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of SO_x (SO_2 and SO_4) and particulate matter (PM) were estimated from the duration, route, engine power, and load of each ship journey using the SO_x and PM emission factors derived from the second International Maritime Organization greenhouse gas study [Buhaug *et al.*, 2009]. The BC and organic carbon (OC) component emission rates were derived from the PM speciation fractions of Lack *et al.* [2008] and Lack *et al.* [2009]. The Corbett *et al.* [2010] inventory does not include fishing vessels, so these are omitted in the present study. The impact of this omission is discussed below.

[10] The seasonally resolved Corbett *et al.* [2010] inventories (hereafter referred to as C10) were interpolated from a 5×5 km grid to a spatially inhomogeneous $1^\circ \times 1^\circ$ grid; thus, the impact of peak concentrations is likely to be underestimated. However, given the typical modeled BC lifetime of 6.6 days [Mann *et al.*, 2010], we suggest that this effect will be limited. As the inventories cover the Arctic only, they were merged with the global shipping inventories from Aerosol Comparisons between Observations and Models (AEROCOM) [Dentener *et al.*, 2006] by replacing AEROCOM emissions with C10 in model grid boxes where C10 emissions were greater than zero. Where AEROCOM emissions were replaced with C10, primary aerosol and SO_2 emissions increased. The total overlap of the two inventories (grid boxes where C10 has been substituted for nonzero emissions in AEROCOM) is 40%. Excluding emissions south of 60°N , this overlap falls to 1% (0.5% overlap north of 65°N).

[11] Anthropogenic BC emission inventories for non-shipping (5 Tg/yr) were taken from the AEROCOM hindcast database for 2004 [Dentener *et al.*, 2006]. Wildfire emissions were from the Global Fire Emissions Database (GFED) [van der Werf *et al.*, 2003]. In 2004, wildfires emitted 2.7 Tg/yr of BC (0.2 Tg/yr north of 40°N) 0.2σ from the 1997 to 2006 mean (0.5σ north of 40°N). Globally, 34% of BC emissions are attributable to wildfires, 1% to shipping (0.01% to Arctic shipping), and 65% to other anthropogenic sources. For all other aerosol and gas species, emission inventories were identical to those described in Browse *et al.* [2012].

4. Future Emission Scenarios

4.1. Business as Usual (BAU)

[12] The business as usual scenario (BAU) is similar to that described by the Arctic Marine Shipping Assessment (AMSA) [Brigham *et al.*, 2009] as “a healthy rate of Arctic development that includes concern for the preservation of Arctic ecosystems, cultures and shared economic and political interests”. In the BAU scenario, the location of shipping lanes changes little between 2004 and 2050, although the density of traffic increases resulting in a factor of 3 increase in BC emissions.

[13] These emission rates do not include the introduction of controls on BC emissions, which Corbett *et al.* [2010] suggest could reduce BC emissions by 70%. Thus, the results presented here represent the maximum potential impact of BC shipping emissions projected by Corbett *et al.* [2010].

4.2. High Growth Scenario (HiG)

[14] The diversion or high growth (HiG) inventories are loosely based on the low-regulation Arctic-race scenario

described by the AMSA study as “lack of an integrated set of maritime rules and regulations, and insufficient infrastructure to support such a high level of marine activity”. Given the uncertainty as to when sufficient sea ice loss will be frequent enough for large-scale diversions to begin, we assume a 5% diversion of global shipping in 2050 [Corbett *et al.*, 2010].

[15] Legislation concerning shipping fuel standards and sulfate emissions is also included in the HiG and BAU inventories. Thus, in both BAU and HiG simulations, Arctic annual SO_2 emissions decrease between 2004 and 2050 (2500 Mg less than in 2004). A decrease in SO_2 emissions could slow the rate of H_2SO_4 uptake onto BC particles, slowing the conversion from insoluble to soluble (cloud active) and increasing the lifetime of BC aerosol. However, any change in BC lifetime caused by changes in SO_2 is more likely to be controlled by SO_2 from natural sources [Gabric *et al.*, 2005; Browse *et al.*, 2013].

[16] As in 2004, both the HiG and BAU inventories were merged with AEROCOM using the method discussed in section 3. North of 60°N HiG BC emissions in 2050 are a factor of 2 higher than the BAU emissions. Extra-Arctic shipping emissions (those not included in the C10 inventories) were kept the same (for 2004) in all runs. Therefore, this study does not take into account the projected increase in global ship traffic for 2050 [Buhaug *et al.*, 2009]. Likewise, non-shipping BC emissions remain the same between runs. However, as global BC emissions are unlikely to remain static over the next 50 years, we examine the impact of low-latitude BC emission decreases on high-latitude BC deposition (section 7).

4.3. Experimental Setup

[17] To quantify the contribution of shipping emissions to Arctic BC deposition, three core simulations were used:

[18] 1. **PD** - a present-day run based on 2004 meteorology and a 2000 sea ice climatology, using the merged AEROCOM and C10 shipping inventories discussed in section 3.

[19] 2. **BAU** - a run identical to PD but with merged AEROCOM (2004) and BAU shipping inventories from 2050 discussed in section 4.1.

[20] 3. **HiG** - a run identical to PD but with merged AEROCOM (2004) and HiG shipping inventories from 2050 discussed in section 4.2.

[21] For all simulations, the meteorology (diagnosed from European Centre for Medium-Range Weather Forecasts output) and non-shipping emission inventories were from 2004 and kept identical between the runs. In addition, two sensitivity simulations were performed in which either Arctic or extra-Arctic shipping emissions were set to zero (PD-no-AS and PD-no-eAS runs, respectively). Finally, a run for 2004 was completed in which wildfire emissions were set to zero so that the contribution of shipping to anthropogenic high-latitude BC deposition could be quantified.

5. BC Deposition From Shipping in 2004

[22] Analysis of deposition rates between PD and PD-no-AS shows that Arctic shipping results in 752 Mg/yr of BC deposition north of 60°N (85% of C10 emissions), with 80 Mg/yr and 286 Mg/yr deposited on sea ice and land surfaces, respectively. The deposited BC mass north of

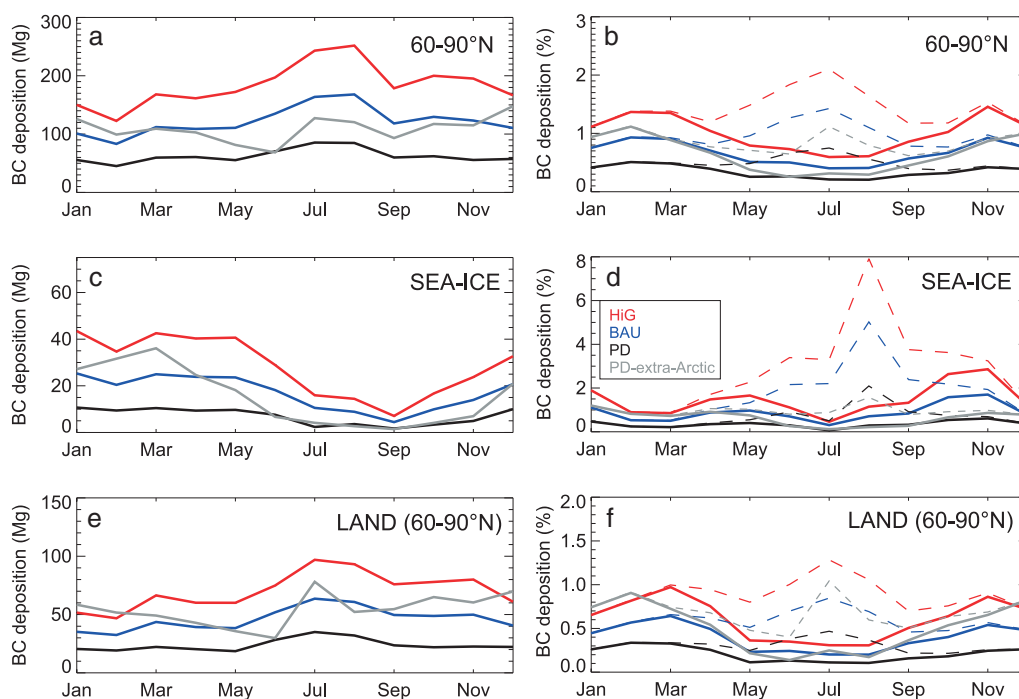


Figure 1. Monthly deposited BC (a, b) north of 60°N , (c, d) over sea ice, and (e, f) over land north of 60°N attributable to present-day (PD) Arctic shipping in 2004 (black), BAU Arctic shipping in 2050 (blue), HiG Arctic shipping in 2050 (red), and extra-Arctic shipping in 2004 (grey). The percentage (Figures 1b, 1d, and 1f) of deposited BC attributable to shipping sectors is shown relative to the total BC deposition (solid lines) and the anthropogenic component of deposited BC (dashed lines).

60°N from Arctic shipping is greatest in July (85 Mg/yr). However, on sea ice, this seasonal cycle is inverted (Figures 1a and 1c).

[23] Annually, Arctic shipping contributes 0.3% to the BC mass deposited north of 60°N (250 Gg). In addition, we estimate that about 50% of modeled BC deposition is on open ocean. Our results suggest that reducing current Arctic ship traffic will not significantly decrease BC deposition on central Arctic sea ice (Figure 1d). However, on the west coast of Greenland, 6%–8% of deposited BC originates from local ship traffic (Figure 2).

[24] Extra-Arctic shipping contributes more BC mass to deposition north of 60°N (1300 Mg) than Arctic shipping (752 Mg), equivalent to 0.5% of the total BC mass.

However, we must consider that 32% of high-latitude ship sourced BC deposition (2000 Mg) originates from less than 1.0% of global shipping emissions. Thus, regulation of Arctic shipping could yield a reduction in near-Arctic BC aerosol that leads to a greater decrease in high-latitude BC deposition than a similar control strategy applied only to the extra-Arctic shipping industry.

[25] Our inventories exclude the contribution of Arctic fishing emissions. Corbett *et al.* [2010] report that 29% of emissions in 2004 originate from fishing. Assuming all BC emitted by the fishing industry is deposited locally, BC deposition north of 60°N would increase from 752 to 1059 Mg and the contribution of Arctic shipping to high-latitude BC deposition to 0.4% (0.7% of anthropogenic BC deposition).

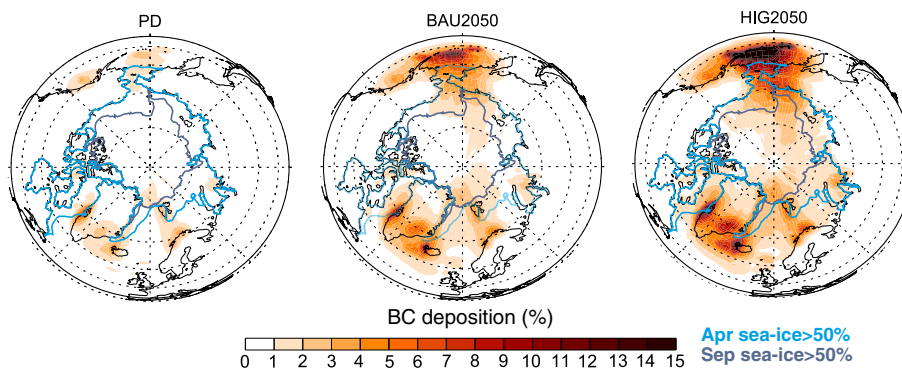


Figure 2. Contribution of Arctic shipping emissions to annual BC deposition in 2004 (left) and 2050 for the BAU (middle) and HiG (right) shipping scenarios. Also shown is the 2000 sea ice edge (sea ice fraction $> 50\%$) in April (maximum) and September (minimum).

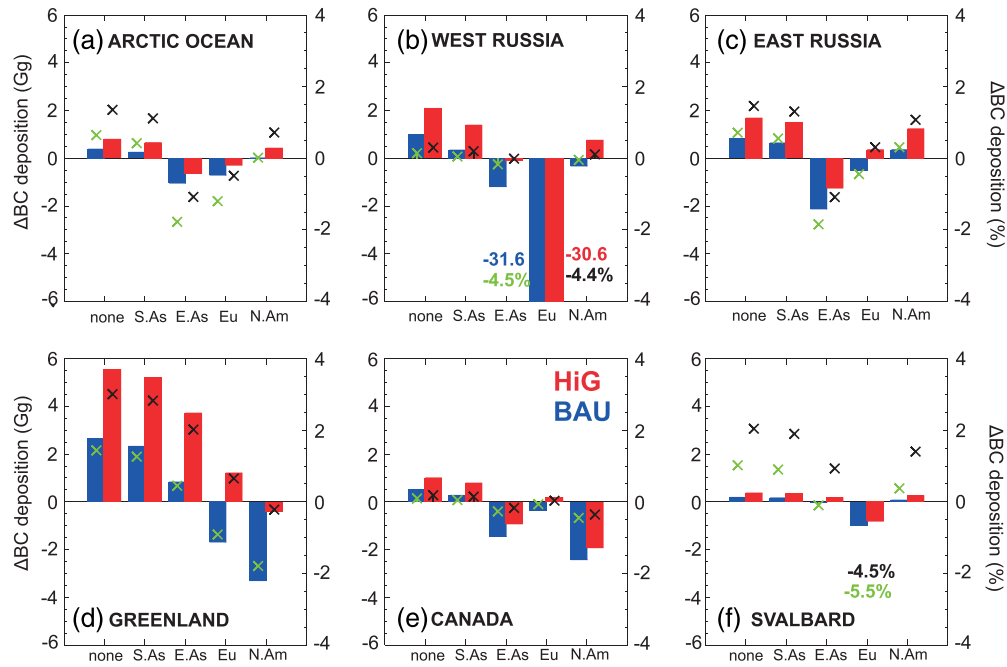


Figure 3. (a–f) Change in annual BC deposition between 2004 and 2050 over six different regions for the BAU (blue) and HiG (red) shipping scenarios and five different mitigation strategies: no mitigation (none), 10% reduction in South Asian BC emissions (S.As), 10% reduction in East Asian emissions (E.As), 10% reduction in European emissions (Eu), and 10% reduction in North American emissions (N.Am). The absolute change (left axis) is shown as the bars while the percentage change (right axis) is shown by the green (BAU) and black (HiG) crosses.

Thus, even when accounting for Arctic fishing emissions, the overall impact of Arctic shipping on high-latitude BC deposition remains low.

[26] Uncertainty in modeled BC deposition has two principal sources. For BC derived from Arctic shipping, the main source of uncertainty is from the emissions themselves [Corbett *et al.*, 2010]. Based on the high-low ratio of estimated emission factors (BC emission per kWh) reported by Buhaug *et al.* [2009] combined with discussion in the literature [Buhaug *et al.*, 2009 and reference therein], we estimate a factor of 3 upper bound on our inventories, increasing Arctic shipping emissions in 2004 to 2640 Mg.

[27] For aerosol transported to the Arctic from lower latitudes, the main sources of uncertainty are atmospheric processes that affect long-range transport [Browse *et al.*, 2012; Lee *et al.*, 2012]. The Lee *et al.* [2012] uncertainty analysis of GLOMAP accounting for 28 parameters and emissions has been extended to BC (unpublished results). We estimate that Arctic BC concentrations from extra-Arctic sources have a 1σ uncertainty between $\pm 70\%$ in the winter and $\pm 40\%$ in the summer.

[28] Taking the lower bound estimate for transported BC, the upper bound estimate for shipping emissions (factor of 3) and assuming that this increase in ship emissions affects only the Arctic, we calculate that Arctic shipping contributes a maximum of 1.9% to annual BC deposition north of 60°N in 2004.

[29] The dominant contribution of BC aerosol mass from extra-Arctic shipping (and non-shipping) emissions to Arctic BC deposition is consistent with modeling [Browse *et al.*, 2012] and observational studies [Garrett *et al.*, 2011] and arises from efficient long-range transport processes [Stohl, 2006], low local scavenging rates [Browse *et al.*, 2012], and

reduced local emissions [Corbett *et al.*, 2010] during the Arctic winter and spring. Although aerosol is initially transported largely at higher altitudes the surface-level BC is also strongly affected by these processes [Browse *et al.*, 2012], as demonstrated by the strong seasonal cycle in aerosol mass concentrations at Arctic ground sites. Local reductions in ship traffic may have a regional impact, particularly on the West Coast of Greenland (Figure 2). However, to reduce present-day deposition of BC in the Arctic, extra-Arctic shipping emissions need to be considered alongside Arctic.

6. BC Deposition From Shipping in 2050

[30] The absolute increase in BC deposition north of 60°N is consistent with the emission increase from 2004 to 2050 for both the BAU and HiG scenario, increasing the percentage of Arctic ship emissions deposited north of 60°N from 85% to more than 95% in 2050. Overall, the HiG scenario deposits approximately twice as much BC per year north of 60°N than the BAU. However, in the BAU and HiG scenarios, the total BC deposition averaged north of 60°N from Arctic shipping remains small, increasing to only 0.4% and 0.7%, respectively. Using our lower and upper bound estimates for transported BC and Arctic shipping emissions (see above), we project a maximum contribution of Arctic shipping in 2050 to high-latitude BC deposition of 5% (assuming no change in extra-Arctic emissions).

[31] Over the west coast of Greenland and the Bering sea, the BC deposition from shipping emissions rises to 10%–15% in the HiG scenario (Figure 2). Thus, future shipping BC emissions could have a significant impact on the albedo of the sub-Arctic. Our results suggest that the impact of local shipping near the vulnerable Greenland ice sheet may be

significant. However, as we show below, control of distant sources may be of greater priority to reduce high-latitude BC deposition.

7. BC Deposition From Non-Shipping Emissions

[32] The HiG scenario projected for Arctic shipping emissions results in an increase in BC deposition north of 60°N of 0.5% (0.9% on sea ice, 0.3% on land). However, increases of as much as 15% occur in the sub-Arctic and close to heavy ship traffic (Figure 2). Thus, several mitigation strategies were simulated to (1) confirm that extra-Arctic sources other than shipping contribute significantly more to BC deposition than Arctic shipping and (2) to determine whether BC deposition from Arctic shipping emissions can be offset by reducing non-shipping emissions at lower latitudes. The model was run with BAU and HiG 2050 shipping emissions in combination with a 10% decrease in BC emissions from the industrial regions discussed in the Hemispheric Transport of Air Pollution report (www.htap.org).

[33] Figure 3 shows the change in 2050 BC deposition (assuming BAU and HiG shipping) over six Arctic regions (discussed in Doherty *et al.* [2010]) including Greenland. Over Greenland, a 10% reduction in North American emissions results in a regional reduction in BC deposition (despite increased ship traffic) (Figure 3d) but does not offset the impact of Arctic shipping on sea ice (Figure 3a) or the eastern continental Arctic (Figures 3b and 3c). However, this solution assumes implicit equalization of these mitigation options, which is an unlikely scenario.

8. Conclusions

[34] We used a global model of aerosol processes (GLOMAP) combined with new shipping inventories for 2050 [Corbett *et al.*, 2010] to quantify the relative contribution of Arctic shipping emissions to high-latitude BC deposition in 2004 and 2050. BC emissions from shipping were found to contribute 0.3% to the total BC mass deposited north of 60°N (0.5% of the anthropogenic BC mass) in 2004 and 0.7% (1.4% of the anthropogenic) in a 2050 high growth scenario (Figure 1). However, regional impacts were found to be higher.

[35] Over Greenland, the deposited BC mass attributable to high growth shipping emissions in 2050 is 10%–15% (Figure 2). This increase in regional BC deposition can be mitigated by a 10% decrease in North American BC emissions (Figure 3d). However, reductions in one lone region are insufficient to reduce BC deposition over the entire Arctic (Figure 3).

[36] Our results imply that future shipping emission increases are sufficiently small that over the entire Arctic, they are unlikely to be measurable against natural emission variability from wildfires, changes in transport efficiency, or reductions in lower latitude anthropogenic emissions, which will also reduce the remote Arctic forcing resulting from midlatitude BC aerosol concentrations [Sand *et al.*, 2013; Flanner, 2013]. Thus, to achieve desired Arctic BC deposition reductions, controls over distant stationary sources, which may be more likely due to existing air quality standards, should be considered alongside international agreements controlling shipping emissions.

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